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AN OPTIMIZATION ALGORITHM FOR TRUCKS DISPATCHING IN AN OPEN PIT MINE

by

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ABSTRACT

We propose an advanced truck dispatching system using mathematical optimization algorithms. This model uses integer programming, a non-linear cost network and an assignment problem. The system improves operation control compared to existing algorithms. Furthermore, it provides planning tools for choosing equipments and tradeoff between quality and quantity of production.

Key-words: open pit; mines; truck dispatching.

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RÉSUMÉ

Nous proposons un système avant-gardiste d'assignation en temps réel des camions dans une mine à ciel ouvert utilisant des techniques d'optimisation mathématiques : programmation en nombre entier, réseaux à coût non linéaires, problèmes d'affectation, etc. Ce système assure une utilisation de l'équipement disponible meilleure que celles obtenues avec les algorithmes existants. De plus, il fournit des outils de planification pour le choix et la localisation des équipements et pour trouver un équilibre économique entre les objectifs de quantité et de qualité de la production.

Mots-clés : mine à ciel ouvert; affectation; camions; temps réel.

1. INTRODUCTION

In the past few years, a number of truck dispatching systems were developed for open pit mines : [White 81], [Young 84], [Orisek 86]. Generally, to ensure the control, a sophisticated telecommunication equipment is used to detect the true working time of trucks and shovels. A computer uses this information to assign trucks to shovels in order to maximize production and/or to control the quality of the ore produced. Production is then the principal target of the control. However, prior to production, a planning function has to be undertaken to select among the available equipment (trucks and shovels) the ones which will be operable and the areas to be worked in the mine. Obviously, the quality of the choices made at the planning stage affects the quality of the dispatching since it determines the difficulty of the control problems and, consequently, the resulting productivity. Therefore, we propose an advanced dispatching system integrating both the planning and control functions.

2. GENERAL DESCRIPTION OF THE SYSTEM

Figure 1 schematically illustrates the system and its interaction with the mine environment. The computer system handles all three steps in the production planning process : the choice of equipment, the calculation of the operational plan, and the automatic truck dispatching.

The planner is reponsible for the first two steps. He first chooses which pieces of equipment should be operated to satisfy production and quality objectives. This is done interactively with the computer using the "equipment choice" module. When the equipment has been chosen, the system enters the "operational planning calculation" module in which production estimates are calculated. The planner may then modify the objectives, revise equipment choice and recalculate production, or he may accept the plan provided. The accepted plan is transferred to the "dispatching" module where it serves as a criterion for truck assignment.

The dispatching module is directly linked to production. It interacts first with the mine, by tracking the position of trucks and transmitting truck assignments via a telecommunications channel. It also interacts with the dispatcher who can observe the movement of trucks on a screen and can enter information on equipment breakdowns to the computer.

2.1 Choice of Equipment

The first step in the planning-production process consists in selecting the equipment to be used to reach the quantity and quality objectives: the number of trucks, the number of shovels and the areas to be worked in the mine.

There is usually little flexibility to determine the number of trucks; the drivers have to be advised ahead of time about their working schedule. The number of trucks considered is given an an input parameter

meter. A few drivers may be added at the last minute if necessary to meet the objectives, providing some operable trucks are available. If there are more trucks than required, some of them may be temporarily halted. In such cases the input parameter is modified and the process is started all over again.

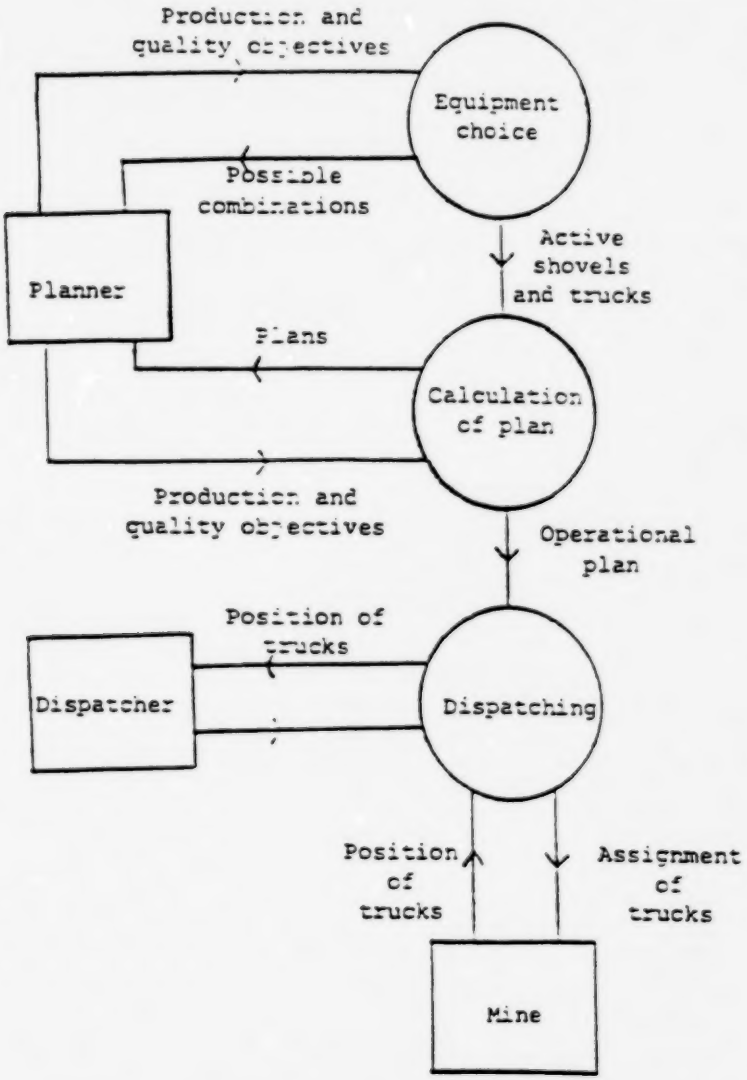


Figure 1: Diagram of the system

The set of operational shovels and their location in the mine are known. Each shovel has access to several benches of material with different properties (from one to four benches). Note that it is not easy to move a shovel over a large distance as these are electric shovels powered through cables. The work schedules give the number of shovel operators available and it will generally be desired to have them all working. So the problem consists of determining the active shovels and the benches to which they should be assigned in order to satisfy the quantity and quality objectives as far as possible.

This problem can be approximated by a linear programming model with integer variables expressing the quality objectives as constraints. The formulation uses the following parameters:

$\{i/i=1,\ldots,I\}$: the set of available shovels.

$\{j/j=1,\ldots,J_i\}$: the set of ore benches accessible to shovel i.

$\{k/k=1,\ldots,K\}$: the set of quality factors considered (content, rate of impurities, etc.).

T_{ij}^k : value of the k^{th} quality factor of the ore in bench j accessible to shovel i.

A^k, B^k : minimum and maximum acceptable values of the k^{th} quality factor in the extracted ore.

N : number of shovel operators available.

C : maximum production of a shovel.

The variables of the problem are the following:

p_{ij} : rate of production of shovel i in bench j.

x_{ij} : binary variable taking value 1 if shovel i is operating in bench j.

The model is formulated as follows:

$$\max \quad C \sum_{i=1}^{I} \sum_{j=1}^{J_i} p_{ij} \qquad [1]$$

$$\sum_{j=1}^{J_i} x_{ij} \leq 1 \qquad i=1,\ldots,I \qquad [2]$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} x_{ij} \leq N \qquad [3]$$

$$x_{ij} \in \{0,1\} \qquad [4]$$

$$0 \leq p_{ij} \leq x_{ij} \qquad i=1,\ldots,I,\ j=1,\ldots,J_i \qquad [5]$$

$$A^k \leq \sum_{i=1}^{I} \sum_{j=1}^{J_i} p_{ij} T^k_{ij} / \sum_{i=1}^{I} \sum_{j=1}^{J_i} p_{ij} \leq B^k \quad k=1,\ldots,K \qquad [6]$$

The objective [1] maximizes the production, constraint [2] limits each shovel to only one bench, constraint [3] limits the number of active shovels to the number of operators. Constraint [5] ensures that the production rate is null if the shovel is not active in this bench and between 0 and 1 if it is active in it. Finally, constraint [6] ensures that the content of the ore is between the limits for each quality factor.

This problem with binary variables is very difficult to solve because in relaxing the integrity constraint [4] it is generally possible to obtain the maximum production C·N while satisfying the quality constraints by using fractions of shovels working in more than N positions. Such fractional solutions at 100% of production may also be obtained even if many variables were set in the listing tree. The resolution by implicit listing is then very little efficient: it is necessary to go down very deeply in the tree before finding integer solutions and there is practically no elimination by bounds on account of the numerous fractional solutions of 100% of production.

On the other hand, if binary variables x_{ij} are fixed, the residual problem [1], [5], [6] can be solved very efficiently. As a matter of fact, with the dual algorithm of the Simplex some optimal solutions are obtained after 2-3 pivots by using as initial solution production rates $p_{ij} = x_{ij}$. This is much faster than with a primal algorithm using as initial solution production rates $p_{ij}=0$. Effectively, the optimal solutions searched are much closer to the maximum production C•N than the null production.

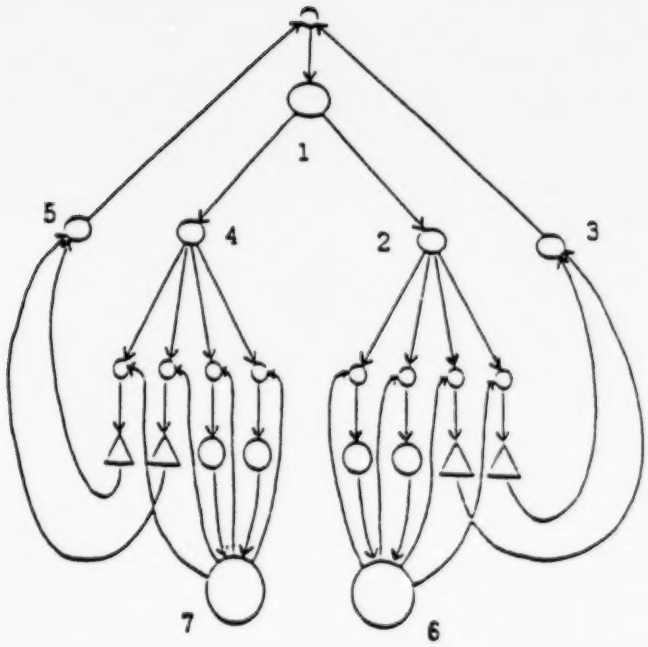
To solve the global problem [1] to [6], we propose an approach which combines the calculating power of the computer with the operator's judgment. The computer is used to evaluate the maximum production satisfying the quality constraints for various combinations of shovel positions. By using the dual algorithm more than 2000 combinations per minute can be evaluated on a PDP-11. The operator reduces the number of combinations of shovel positions by setting parameters which describe the type of solutions desired. He determines the number of shovels operating in the ore, the number in the waste, and the number in each mine. He also limits the choices of benches for each shovel according to priorities and preferences. The operator then asks the computer how many combinations are possible under these conditions and obtains an estimate of the calculation time required to evaluate them all. If the calculation time is found reasonable, the operator requests the evaluation and obtains the best combinations in the decreasing order of production. If the calculation time is deemed too long, the operator may detail his preferences in order to reduce the possibilities. If the best combinations of locations evaluated are not satisfactory productionwise, the operator may modify his preferences to explore other locations.

This planning step is undertaken at the beginning of shifts if the objectives, the number of shovel operators or the number of truck drivers are changed. It is also made as required during a work shift in case of modifications to working conditions due to equipment breakdown or other disturbances.

2.2 Operational Plan

The second step of the planning process consists in determining the operational plan for the equipment selected. The number of trucks, the number of shovels and their location are fixed. The plan determines the activity level of each shovel and the routes travelled by the trucks to best meet objectives concerning the quantity and quality of ore transported. At this step, we propose a more realistic model of the ore transportation problem than that provided by the linear programming models of the planning stage. Linear models such as the one proposed by White [83] do not consider the increased waiting time which occurs when the capacity limits of the shovels or the crusher are approached. In addition, they handle the quality requirements by setting upper and lower limits on the grade of the ore and other characteristics of the mixture. Such models produce extreme solutions: some shovels will work at their maximum capacity, while others will be very little used. In some cases, two shovels in the same type of ore may have quite different activity levels. In addition, solutions are generally at the limits of acceptable quality intervals. These solutions are acceptable as a first approximation to be used in determining the location of the shovels, but they cannot be used for generating an operational plan in real time.

To obtain a more realistic plan, we propose a non-linear programming model which takes into account the increase in waiting time with the congestion of the shovels and the crusher, and which produces a better equilibrium between quantity and quality objectives. The extraction plan is determined by solving a network problem with nonlinear costs. An example of a network is shown in Figure 2.



waste shovels
ore shovels
waiting nodes

1 - crusher
2 - entrance of mine "A"
3 - exit of mine "A"
4 - entrance of mine "B"
5 - exit of mine "B"
6 - waste pile "A"
7 - waste pile "B"

Figure 2: Structure of Mont-Wright mine network

Let us now introduce the following:

N : the set of the network nodes: crusher, shovels, waste piles, waiting nodes, crossroads.

P : the set of travel arcs (routes between the nodes).

A : the set of waiting arcs, connecting the waiting nodes to the shovels and to the crusher.

B : the set of all the arcs $B = A \cup P$.

AM : the subset of the waiting arcs incidental to the ore shovels.

AS : the subset of the waiting arcs incidental to the waste shovels.

AP : the set of all waiting arcs to shovels $AP = AM \cup AS$.

Θ_i : the set of the arcs of B having node $i \in P$ as origin.

T_i : the set of the arcs of B ending at node $i \in P$.

M_a : for $a \in AP$, M_a indicates the maximum number of trips that can be loaded by shovel accessible through this arc.

Let us introduce the variables:

x_a : the number of truck trips during the planning stage on arc $a \in B$.

A first term of the objective ensures that the production is maximized taking into account the capacity of the shovels. This term also ensures a much better dispatching of shovels than the ponderated sum of the production of each shovel. Parameters V_1 and V_2 allow a different ponderation of the ore and waste productions.

$$C_1(X) = V_1 \sum_{a \in AM} (X_a - M_a)^2 + V_2 \sum_{a \in AS} (X_a - M_a)^2 \qquad [7]$$

A second term ensures that the number of trucks used is equal to the number available. The operating time includes the loading and unloading times, the travelling times, and the waiting times.

$$C_2(X) = V_3 \left(\sum_{a \in AP} (C_a + D_a) X_a + \sum_{a \in P} d_a X_a + \sum_{a \in A} A_a (X_a) X_a - D \right)^2 \qquad [8]$$

The parameters C_a and D_a are the average loading and unloading times for the shovel accessible by arc a. The unloading time can be associated with the shovel because the unloading point is determined by the loading point. The parameter d_a is the average travelling time of arc a. The function $A_a(X_a)$ measures the average waiting time of the trucks on arc a. This is a non-linear increasing function of X_a derived from queuing theory. The parameter D corresponds to the availability D = number of trucks multiplied by the duration of the planning period. The parameter V_3 is adjusted during the solution process to obtain the desired precision of the operating time of the trucks.

Other terms are added for each quality objective

$$C_3(X) = \sum_{k=1}^{K} f_k \left(\sum_{a \in PM} T_a^k X_a \Big/ \sum_{a \in PM} X_a \right) \qquad [9]$$

The function $f_k(\cdot)$ is applicable to each quality objective. The constant T_a^k is the value of the k^{th} quality factor of the ore loaded by the shovel accessible by arc a.

For example, to achieve the desired average grade, a penalty function is used as shown in Figure 3.

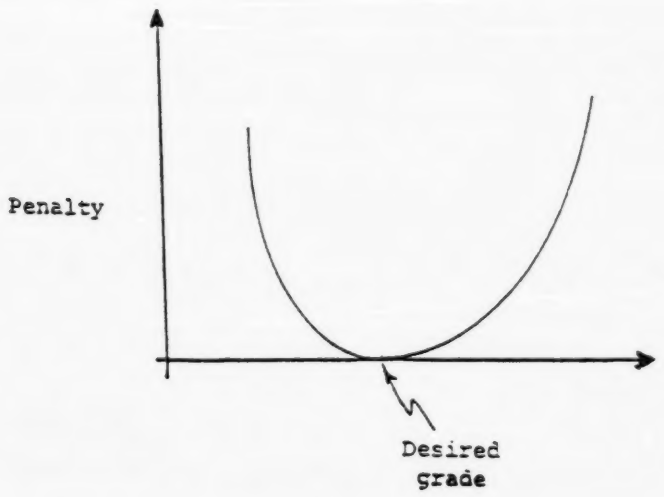


Figure 3: Penalty associated with deviations from desired grade

The right branch measures the value of the iron lost in the tailings of the concentrator whenever the grade of the ore exceeds the value for which it is adjusted. The left branch measures the loss of quality of the concentrate and the reduction in the sales price when the ore grade decreases. The model thus realizes the economic equilibrium between tonnage and quality. Tonnage is reduced to increase quality only if this is profitable.

The operational plan is the solution to the following problem:

$$\min C_1(X) + C_2(X) + C_3(X)$$

$$\sum_{a\in B^+(i)} X_a - \sum_{a\in B^-(i)} = 0 \qquad i\in N \qquad [10]$$

$$0 \leq X_a \qquad a\in B.$$

The constraint [10] ensures that the flow of trucks is maintained. $B^+(i)$ is the set of arcs entering node i, while $B^-(i)$ is the set of the outgoing arcs.

This network problem with non-linear costs is quite easily solved. For a mine with 15 shovels and 5 unloading points the network includes 40 nodes and less than 100 arcs. A network of this size requires less than 4K bytes of memory and can be handled by a small computer. We have developed a specialized version of the reduced gradient method to solve this problem. Our algorithm adjusts the various parameters during the solution process to achieve a solution with the desired accuracy. A solution giving the optimal number of trips on each route to three significant figures is obtained in ten seconds on a PDP-11.

This non-linear cost model has the advantage of producing operational plans which are much more stable than linear models in the face of parameter modifications. Fig. 4 shows an example of this quality of the module; the numbers of trips per shovel vary quite regularly as a function of the total number of trucks used in the planning calculations. This stability simplifies the task of the operator who adjusts the operating parameters to obtain a plan which meets production objectives.

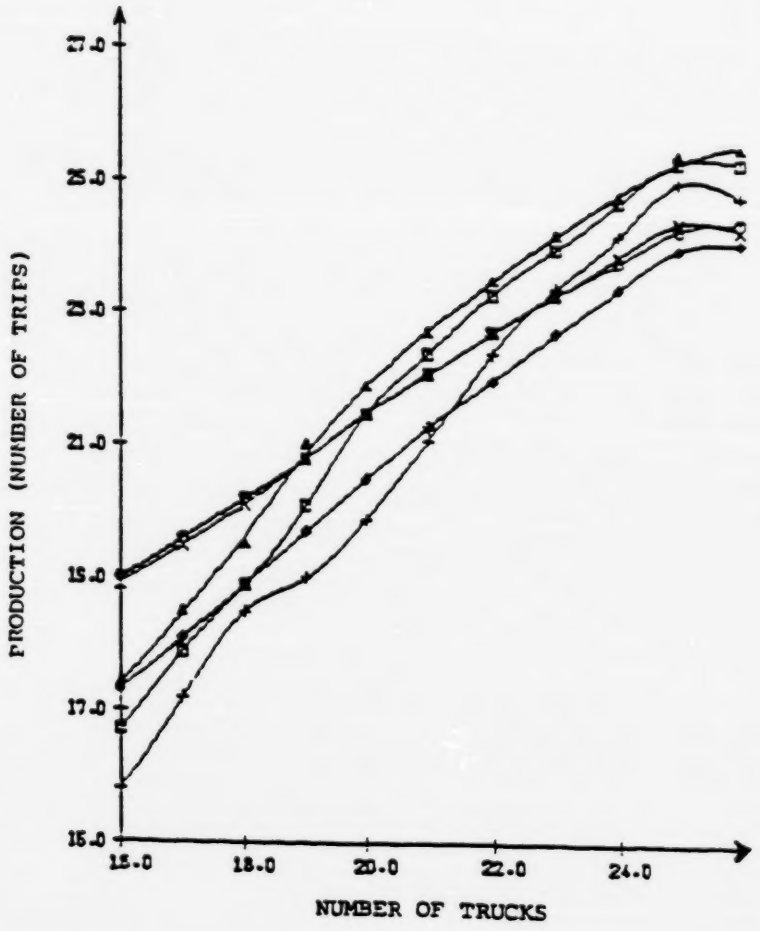


Figure 4: Number of trips per shovel as a function of the number of trucks

2.3 Automatic Truck Dispatching

The last step in the decision process determines the real time assignment of trucks. After each unloading, the system communicates to the truck its next loading point. After loading, the truck proceeds to the unloading point which has been previously fixed for each shovel. These assignment decisions are taken so as to implement the operating plan as far as possible and thus to obtain the best performance in terms of the quantity and quality objectives.

The dispatching system first serves a communication function. This function includes the determination of the position of the trucks, the evaluation of travel and loading times, and the estimation of the times at which each truck and each shovel will become available; the system also ensures the communication of truck assignments. Fig. 5 illustrates the equipment used.

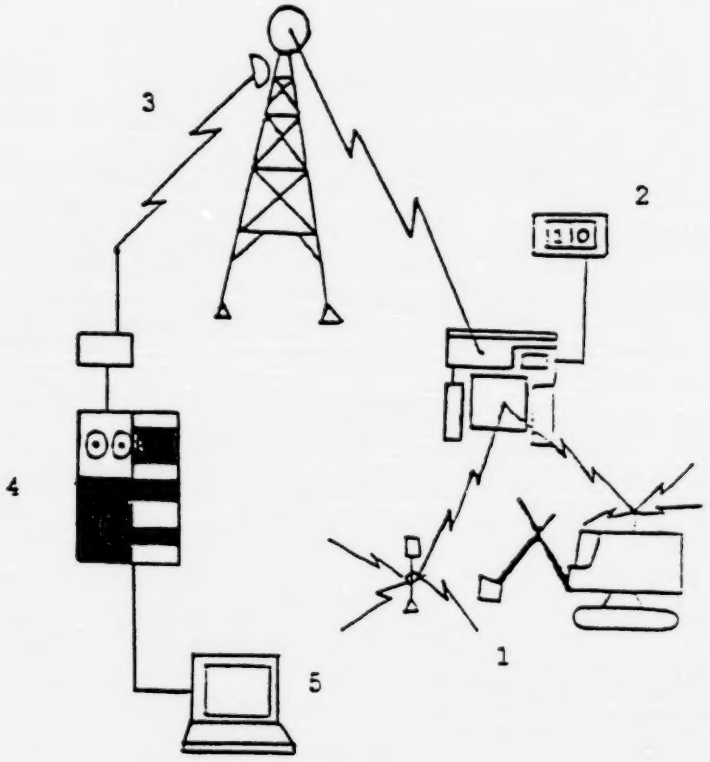


Figure 5: The communication system.

Radio transmitters (1) are placed at strategic locations in the mine (road intersections, shovels, dump entrances, etc.). Each transmitter emits a unique signal which is recorded in the black box of a truck (2) as it passes the transmitter. The transmitter (3) enables the truck to inform the computer (4) of the contents of the black box. This information is processed by the computer to establish the position of trucks and to

display all necessary information on the dispatcher's terminal (5). As the computer knows the location of all the trucks, it also knows when they will require a new assignment. The computer (4) determines the assignment and transmits it to the truck via the communication radio (3), displaying the code associated with the truck's new destination on the numerical screen (2).

The decision method developed for this step considers both the truck to be assigned and the trucks which will next become available. It thus optimally assigns around ten trucks to the next shovels to become available. This is a major improvement over the Charlemagne system then used at Mont-Wright, and several other systems which consider only the first truck [Charlemagne 79]. These short-term sighted approaches may produce decisions which are quite far from the optimum.

Let us introduce the notation required for the formulation of the assignment problem:

$\{c=1,\ldots,C\}$: the set of next trucks to become available.

$\{p=1,\ldots,P\}$: the set of next shovels to become available.

A : the set of assignment arcs.

The arc (c,p) is included in A if the route from the unloading point of truck c towards shovel p is used in the operational plan.

Z_{cp} : binary variable taking value 1 if truck c is assigned to shovel p.

A_p^1 : average waiting time of a truck at shovel p as calculated by the plan.

A_p^2 : average waiting time of shovel p between two trucks as calculated by the plan.

E_{cp}^1 : expected waiting time of truck c when assigned to shovel p.

E^2_{cp} : expected waiting time of shovel p when truck c is assigned to it.

The expectations E^1_{cp} and E^2_{cp} are calculated from the information in real time received by the computer on the truck locations and on the travel and loading times. Erlang's distributions are used for this calculation.

C_{cp} : the cost for assigning truck c to shovel p measuring the deviation with respect to the plan is defined by the following formula:

$$C_{cp} = (E^1_{cp} - A^1_p)^2 + E^2_{cp} - A^2_p)^2 \ . \qquad [11]$$

The assignment problem is formulated as follows:

$$\min \sum_{c=1}^{C} \sum_{p=1}^{P} C_{cp} \, z_{cp} \qquad [12]$$

$$\sum_{c=1}^{C} z_{cp} \leq 1 \qquad p=1,\ldots,P \qquad [13]$$

$$\sum_{p=1}^{P} z_{cp} = 1 \qquad c=1,\ldots,C \qquad [14]$$

$$z_{cp} \in \{0,1\} \qquad c=1,\ldots,C, \ p=1,\ldots,P \ . \qquad [15]$$

The objective measures the total deviation with respect to the plan, constraint [13] ensures that each shovel receives at the most one truck and constraint [14] ensures that each truck is assigned to only one shovel.

One of the main innovations of this model resides in its objective that ensures the truck assignment in accordance with the plan while taking advantage of the uncertainties in the operating times.

Other models propose an objective based on the difference between the estimated time of arrival of trucks at the shovel and the expected time according to the plan [White, 83]. The expected time is given by the frequencies established in the plan assuming that trucks are equally spaced.

This method does not take advantage of more rapid loadings to send more trucks. In addition, it keeps on sending trucks at the same frequency even if loading time is longer than expected and trucks are kept waiting. Such a measure will generate operating problems for very busy shovels which have highly variable loading times. With the proposed objective, our model tries to reproduce the waiting times of the shovels and trucks which have been calculated by the plan. Figure 6 shows that with this objective the model has a tendency to reproduce the same shaded areas between trucks independently of loading times.

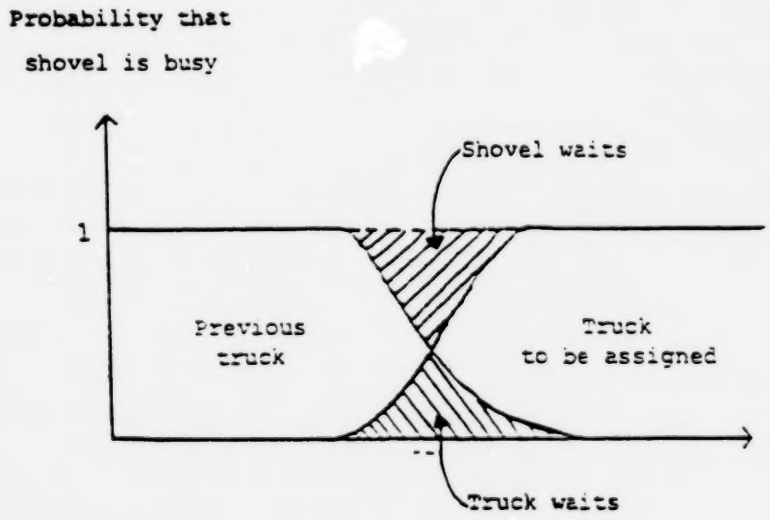


Figure 6: Evaluation of probabilities of waiting time for an assignment

Thus when loading times increase, trucks arrivals are less frequent, and they are more frequent when loading times decrease. On average, trucks arrive with the frequency indicated in the plan, but in addition their spacing is synchronized with fluctuations in the speed of the shovels.

The assignment problem for around ten trucks is solved optimally in less than a quarter of a second on the PDP-11. This problem is solved each time a truck becomes available for assignment. The assignment problem is solved using the following procedure by a shifting horizon method.

Truck assignment procedure:

1. Questioning of the trucks and estimation of the times at which each truck and each shovel will become available;
2. Solution of the assignment problem for around ten trucks;
3. Communicate assignments to the available truck(s), cancel the assignments of trucks which are still occupied, and return to 1.

3. TESTS

We will see in what follows that the production estimated by the planning model can be achieved in practice using our dispatching model. First, we measured the potential improvements in production at the Mont-Wright due to the use of our models as compared with the Charlemagne system. This test was carried out by comparing actual production with the production forecast by our planning model.

Using statistics concerning mine operations, we chose a period of 2½ hours within which there were no fluctuations in the number of shovels and trucks, and where the grade of the ore at each shovel was constant. Using data on loading, unloading, and travel times, an operational plan was calculated and the results were compared with observed production and waiting times at Mont-Wright under the same conditions. During this period, 6 shovels and 15 trucks were used and the grade objective was 0.31 (±0.005). The results are presented in Table 7.

	PRODUCTION (# trips)			TRUCK WAITING TIME (min)	SHOVEL WAITING TIME (min)	GRADE OF BLEND
	ORE	WASTE	TOTAL			
PLAN	65.4	64.7	130.1	73.3	274.1	.3107
MONT-WRIGHT	65.0	51.0	116.0	267.5	338.7	.317

Table 7: Operational plan vs Mont-Wright.

The operational plan gives 14 more trips than the production actually achieved at Mont-Wright over the same period. This is a difference of 11%. In addition, the grade of the mixture produced at Mont-Wright was 0.317, while the operational plan produced much better quality with

0.3107. It is clear that the increase in productivity is due to the reduction in truck waiting time. In fact, truck waiting time is reduced by 72.5% in the calculated operational plan as compared with actual operations at Mont-Wright.

It is difficult to compare a truck dispatching model with the production obtained using current system. It is impossible to run the two systems in parallel to compare their performance because one single system must communicate assignments to trucks. Similarly, we cannot operate the two systems one after the other in the same conditions; once the ore has been transported, it is no longer there to evaluate the second system.

To obtain a situation in which the two dispatching systems could be compared, we developed a simulation of the mine. The simulator randomly generates the travel times and loading and unloading times for trucks and updates the data bank of the system. It replaces the questioning of trucks which provides information on the times at which the trucks pass the transmitters in the mine. The simulator generates activity times according to Erlang distributions with means and standard deviations corresponding to observed values. Fig. 8 shows the exchange of information between the dispatching algorithm and the simulator via the data bank.

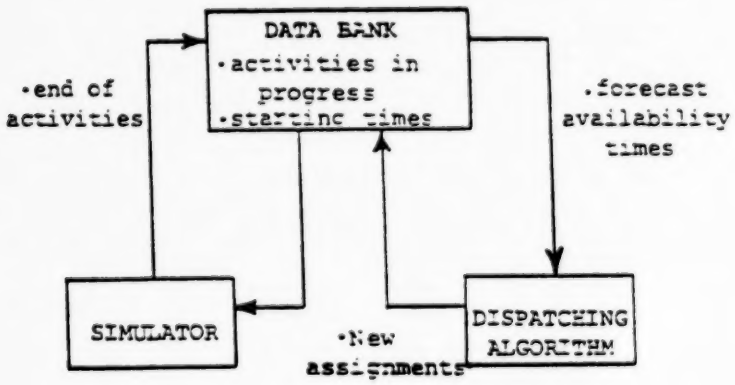


Figure 8: Truck dispatching in a simulated mine

A comparison was carried out between the Charlemagne system and the new dispatching system using the simulator to reproduce 15 hours of typical operations. This duration is divided into 12 periods with different numbers of shovels and trucks, and different activity times. An operating plan was calculated for each period and the simulator was used with the appropriate distributions. The results are presented in Table 9.

	PRODUCTION BY CATEGORY (#TRIPS.)									WAITING TIME (MIN.)					
PERIOD	PLAN			CONTROL			CHARLEMAGNE			PLAN		CONTROL		CHARLEMA	
	OR.	W.	OVE.	OR.	W.	OVE.	OR.	W.	OVE.	TR.	SH.	TR.	SH.	TR.	SH.
23H30-00H30	23.6	19.2	9.4	25	20	9	23	18	7	28	173	31	109	65	99
00H30-2H30	50.4	19.8	23.4	55	17	25	54	17	18	117	147	112	144	157	97
2H30-3H30	20.9	7.45	8.65	20	9	9	21	7	8	15	75	29	75	32	85
3H30-4H30	20.9	7.45	8.65	19	8	10	24	5	5	15	75	19	68	41	90
4H30-5H30	24.7	18.4	8.7	26	20	8	24	20	9	18	130	10	141	15	137
5H30-6H30	20.7	29.7	8.1	20	27	9	21	32	5	29	105	48	108	52	96
6H30-7H30	20.7	29.7	8.1	20	28	7	22	32	5	29	97	30	110	54	97
7H30-8H30	21.5	23.0	8.8	20	24	10	23	25	7	33	77	42	80	43	73
13H30-15H30	34.2	63.8	10.4	34	61	10	37	58	5	36	279	20	273	30	303
16H30-17H30	24.4	10.3	8.5	25	11	7	24	8	7	13	107	37	100	28	90
17H30-18H30	19.5	19.7	11.0	21	19	8	21	20	11	46	52	39	64	60	69
21H30-23H30	37.4	48.6	20.8	35	54	20	39	49	16	97	117	97	117	126	103
TOTAL	318.9	297.1	134.5	320	298	132	333	291	103	476	1434	514	1389	703	1339
	750.5			750			727								

OR. : ORE
W. : WASTE
OVE. : OVERBURDEN
TR. : TRUCK
SH. : SHOVEL

Table 9: Results obtained from the different systems.

Note first that there is a very strong correspondence for each period between the number of trips estimated in the operational plan and those carried out by our dispatching system, both for ore and waste material. In total, this correspondence is even stronger. We may therefore conclude that:

1. The dispatching system follows the plan;
2. The plans are realistic.

Next, note the gain in production of 3.16% over the Charlemagne system. The period of 15 hours with 750 trips is long enough to ensure that the results are significant in spite of the variance in the durations of the simulated activities. Note also that waiting time is reduced by 35% over the Charlemagne system. This gain of productivity is not as substantial as the one of the first comparison. In the comparison with the real situation, the availability of the shovels was rather small and the waiting time of the trucks greater. In this situation, one may observe with Charlemagne a ratio of "truck waiting/shovel waiting" = 4/5 and a 12% waiting of trucks. Our system has reduced this truck waiting from 12% to 3% in this particular case.

In the simulations, the availability of the shovels was greater and the waiting times of the trucks smaller. In this case, we obtain with Charlemagne, a ratio "truck waiting/shovel waiting" = ½ and a truck waiting of 6.5%.

Our system has reduced the truck waiting time from 6.5% to 4%. In short, the gain is less in the second case mostly because the waiting time was smaller on account of the greater availability of the shovels.

4. CONCLUSION

The proposed system gives excellent results in terms of the quantity and quality of ore extracted, and it achieves this with very short computation times through the use of very efficient optimization algorithms. In addition to the operational gains discussed in the text, this system also provides benefits at the planning stage through the use of the first two modules of the system. The equipment choice module and the operational plan establish conditions under which it is possible to achieve both quantity and quality objectives. In fact, rather than discovering at the end of the day that conditions were unfortunately unfavourable, and that objectives could not be met, these modules estimate the production in advance and allow conditions to be modified if it is not possible to satisfy the objectives. In addition, these modules allow objectives to be raised if tests show that it is possible to do better.

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